THE APPLICATION OF RTK-GPS AND STEER-BY-WIRE TECHNOLOGY TO THE AUTOMATIC DRIVING OF VEHICLES AND AN EVALUATION OF DRIVER BEHAVIOR

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Automatic vehicle driving has long been the subject of research efforts designed to improve the safety and efficiency of automobile transportation. In recent years, increasingly sophisticated sensors and automobiles have brought automatic driving systems closer to reality. In this paper we describe an attempt to apply real-time kinematic GPS (RTK-GPS), a highly precise positioning system, and steer-by-wire body technology, which has advanced greatly in recent years, to automatic driving. In addition, we also describe the results of research into human factors related to automatic driving, which will become more and more important as automatic driving is put to practical use.

Key Words: Automatic driving, Intelligent Transport Systems, Advanced vehicle control and safety systems, RTK-GPS, Steer-by-wire

1. INTRODUCTION

This paper describes efforts by its authors related to automatic vehicle driving, a topic that has long been the subject of research efforts designed to improve the safety and efficiency of automobile transportation. Noting the potential for RTK-GPS, the authors were early in advancing research its application to automatic driving. Being interested also in both the potential for steer-by-wire technology and the relationship between automatic driving and drivers, the authors also conducted research on automatic driving and driver assistance using steer-by-wire vehicles and evaluated driver behavior when using automatic driving. The paper below describes the background and objectives of this research.

Let us first address the use of RTK-GPS in automatic driving. Implementing automatic vehicle driving requires detection of the lane in which the vehicle should travel and detection of obstacles, forward vehicles and surrounding vehicles. Proposals for lane detection have included the detection of magnetic markers, radio markers or retroreflective zones laid down on the roadway and the detection of white line markings using vision systems[1-7]. Some of these methods have been to put to practical use as elemental technologies in driver assistance systems. Methods of detecting obstacles, forward vehicles and surrounding vehicles using laser radar, millimeter-wave radar and vision systems[8-11] have also been put to practical use. RTK-GPS is an even more precise form of GPS positioning based on the phase measurement of carrier waves transmitted by GPS satellites and enables positioning to centimeter or millimeter precision. The combination of high-precision positioning information measured using RTK-GPS with high-precision lane position information and information on the position of other vehicles obtained through telecommunications has the potential to substitute for, or supplement, the detection of a lane-center, obstacles, forward vehicles and surrounding vehicles. By using RTK-GPS to achieve lane keeping, vehicle tracking, obstacle avoidance and parking with automatic driving, our research aims to demonstrate that the application of RTK-GPS to automatic vehicle driving can lead to more advanced automatic vehicle driving systems.

Next let us turn to the use of steer-by-wire in automatic driving. Steer-by-wire severs the mechanical connection between steering wheel and steering mechanism, employing sensors to detect steering wheel angle and motors to move the steering mechanism. The "wire" in steer-by-wire refers to an electronic connection. Steer-by-wire is looked to as a promising technology not only because it reduces the number of components and contributes to a lighter vehicle but also because it enables control of the relationship between driver operation of the steering wheel and actual steering angle, improving mobility, handling and stability and making more advanced driver assistance possible[12-16]. By taking advantage of steer-by-wire's independent control of steering wheel angle and actual steering angle to implement both lane keeping support and manual/automatic switching during automatic driving, our research aims to demonstrate that using steer-by-wire can lead to more advanced automatic driving and driver assistance systems for automobiles.

Finally, we address the evaluation of driver behavior when using automatic driving. As with driver assistance systems, it is important to consider system reliability and human factors for automatic vehicle driving systems. Such research has proceeded energetically in the technical field of driver assistance systems and much valuable knowledge has been reported[17-25]. At the same time, although experimentation with actual vehicles is difficult for automatic driving systems, there are examples of evaluations of simulator experiments that extend driver assistance systems to maximize the degree of assistance provided. In looking at human factors in automatic driving systems it is important to evaluate methods of switching between manual and automatic driving, driver ability to monitor automatic driving, and the interfaces for warnings and switching. By identifying the length of time automatic driving is used, driver reaction time and driver behavior during automatic driving, our research aims to present data that can be used in determining how to organize and operate the human-machine interface for automatic driving systems.

This paper is organized as follows. Section 2 presents research on automatic driving using RTK-GPS. Section 3 presents research on automatic driving with steer-by-wire vehicles. Section 4 presents an evaluation of driver behavior when using automatic driving. Section 5 presents our conclusions.

2. AUTOMATIC VEHICLE DRIVING USING RTK-GPS

This section describes research on automatic vehicle driving using RTK-GPS. Automatic driving using RTK-GPS is distinguished in that lane information and the like is described as positioning information rather than obtained through the detection of fixed objects. This makes it easy to create and change driving routes and, through the sharing of positioning information by vehicle-to-vehicle and road-to-vehicle communication, opens up possible applications in coordinating with surrounding vehicles and obstacle avoidance. The following subsections describe research findings in the application of RTK-GPS to the automatic driving control of vehicles, including automatic driving from departure to parking and the use of vehicle-to-vehicle and road-to-vehicle communication for detection of relative vehicle position, vehicle tracking control and obstacle avoidance.

2.1 Fully automatic driving from departure to parking

If the relative position of the automobile and the lane in which it should travel is known, it is possible to automatically control lane keeping by calculating the steering angle and speed required. Automatic parking can be achieved by guiding the automobile to a pre-set location and orientation. In the automatic driving system introduced here, when the driver inputs an on-campus destination, all processes from departure to parking are performed automatically[26]. Figure 1 provides an overview of a test vehicle.

RTK-GPS was used to capture positioning information. The RTK-GPS used was precise to less than 20cm with an update rate of 5Hz. Latitude and longitude information thereby obtained was converted to one-meter unit positioning information originating from the RTF-GPS base station, with the X-axis pointing east and the Y-axis pointing north. In estimating vehicle position and yaw angle 20 times every second, combining the positioning information obtained through RTK-GPS with dead reckoning information based on vehicle movement data such as speed, acceleration, yaw angle speed and sideslip angle also reduced error in position measurement, corrected for RTK-GPS signal processing and data transmission delays and interpolated positioning information[27]. Figure 2 presents the results of the experiment in estimating position. As can be seen, the estimated position correctly interpolated the position measured using RTK-GPS, while also correcting for delay.

Control variables were determined using the vehicle position relative to the positioning information for target routes and target parking spaces stored in the control computer in advance. Information on the position of target routes was stored in the control computer in advance as a sequence of points (XY coordinates) separated by about 15cm. It was easy to measure positioning information for the target routes: simply drive a test vehicle along them at low speed while measuring positioning information and then interpolate, thin and smooth the data sequence as a time-series. Under this system, when the driver selects a destination the route is generated automatically by combining route information for fragments of the site. For example, consider a situation as in Figure 3 where the site to be driven consists of a figure-eight course. In this case there are four areas A through D centered on the labeled points. Routes departing from area A include two routes leading to area B and one route each leading to areas C and D, for a total of four routes. In this way, the site is divided into areas, the area-to-area route fragments are entered and the fragments are combined to generate target routes based on current location and destination. After the target route has been generated, the vehicle automatically shifts from park to drive and starts off. In addition, the system enables the use of a mobile phone to select destination. Using a mobile phone from a remote location to enter one's own position as destination causes the stopped car to start automatically and drive to the destination. In other words, mobile phones can be used to summon vehicles.

The control exercised during driving can be summarized as follows. During each control cycle, route points in the area surrounding the vehicle's current position are derived based on route points for the target course stored in memory. Next, current speed, yaw angle, yaw angle speed and sideslip angle are used to calculate the vehicle's position 1 to 2 seconds in the future assuming current yaw angle speed, sideslip angle and speed are maintained. The deviation between this future position and the target route is obtained, as is the variation in yaw angle speed required to bring this deviation to zero. The necessary variation in yaw angle speed and the deviation between current position and target route are used to derive the necessary change in steering angle, which is then used to control the steering actuator. Speed is controlled based on the curvature of the route and forward obstacle information detected by radar. Figure 5 presents tracking error (lateral displacement), route curvature and speed when driving on routes 1 through 4 as indicated in Figure 4. Tracking error data offers a comparison of results when varying feedback according to curvature and when using fixed feedback gain. As can be seen, varying feedback gain according to curvature results in smaller tracking errors when driving on large-curvature routes. During parking, the vehicle stops along its route near the parking space before automatically shifting into reverse to park. Parking space information (vehicle position and yaw angle when fully parked) is stored in advance as target position and target yaw angle. Steering and speed are controlled to bring current position and yaw angle in line with the targets. Figure 6 illustrates automatic parking using RTK-GPS. The photographs in the upper portion of Figure 6 show parking by a vehicle carrying a driver. The photographs in the lower portion depict a further extension of our research in which the driver gets out of the car on the route and presses a button, causing the unmanned vehicle to detect and park in an open parking space using parking space positioning information combined with information on the distance between surrounding objects obtained using laser radar[28].

In the event that RTK-GPS high-precision measurement becomes unavailable, the vehicle continues to drive using dead reckoning information. In addition, there have also been efforts to compare a database of the positions of white lines, telephone poles and curbs in the driving area with information on such objects detected with a CCD camera to supplement dead reckoning information and serve as a substitute for RTK-GPS in estimating the position of one's own vehicle[29]. Figure 7 shows the absolute value of the difference in measured position using both the method described above and RTK-GPS when driving on routes 1 and 2 from Figure 4. The arrows in the diagram represent sections where visual information was compared with database information. As can be seen, dead reckoning information underwent correction in these sections.

2.2 Detection of the relative position of surrounding vehicles, vehicle tracking control and obstacle avoidance

Using vehicle-to-vehicle communication to share vehicle positioning information obtained using RTK-GPS makes it possible to easily identify the relative position of vehicles[30]. Information on the relative position of surrounding vehicles is effective in controlling following distance and avoiding collisions. In addition, relative position information obtained through the sharing of positional information, unlike that obtained through laser radar or visual sensors, includes information for both surrounding vehicles in all directions and vehicles hidden by obstructed views. For this reason it is effective for the control of merging on expressways, platooning and vehicle tracking systems used to follow forward vehicles. Vehicle tracking systems offer potential laborsaving benefits in the distribution industry by allowing an automatic

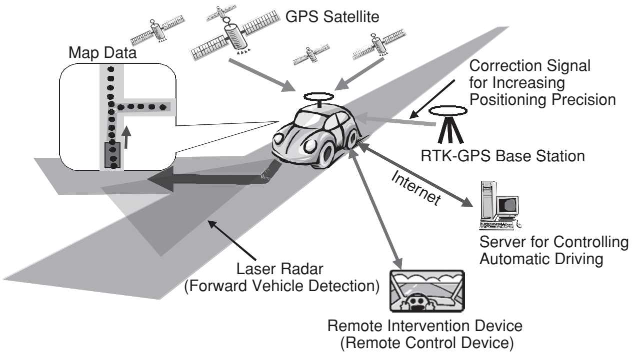

Fig. 1 Automatic driving system using RTK-GPS

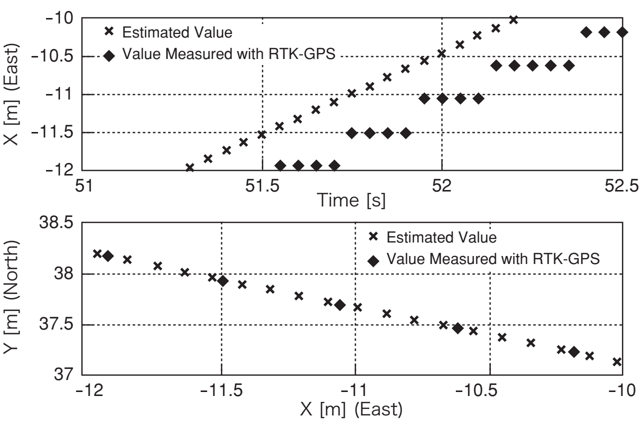

Fig. 2 Estimation of vehicle position
(Above: Time-Series, Below: XY Plot)

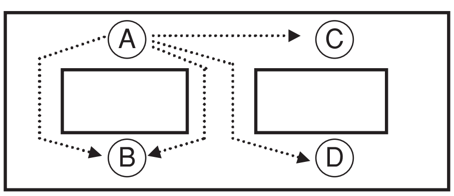

Fig. 3 Target routes

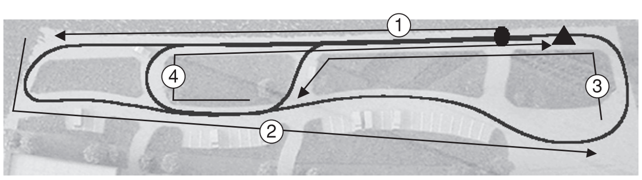

Fig. 4 Routes for driving test

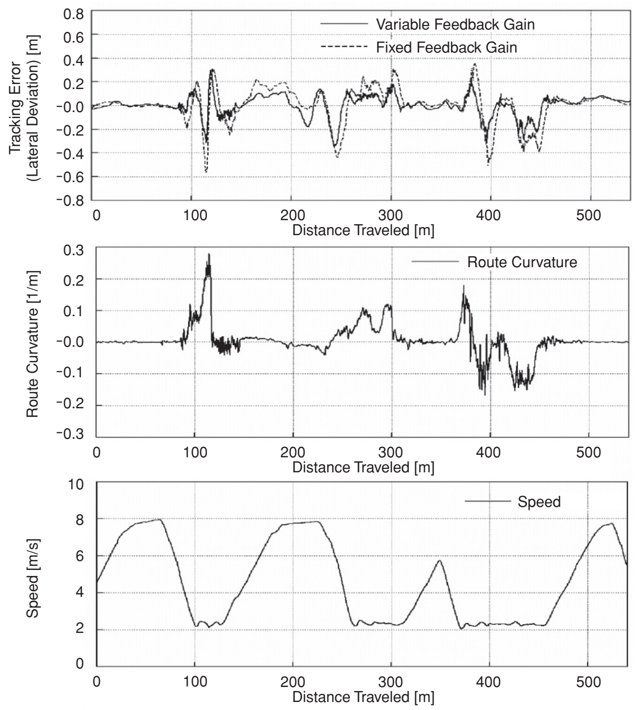

Fig. 5 Results of driving test (Top: Tracking Error, Middle: Route Curvature, Bottom: Speed)

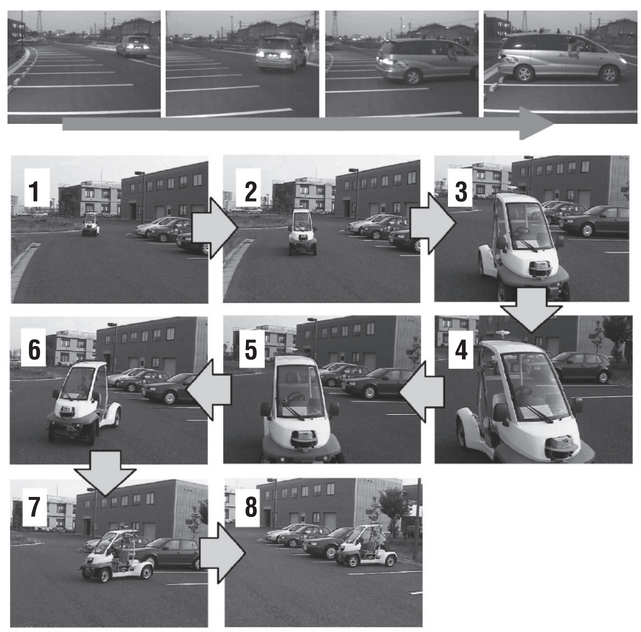

Fig. 6 Automatic parking

driving vehicle to follow in the path of a vehicle operated by a driver. When using radar to detect the forward vehicle in situations where multiple vehicles are following, the vehicles further back exhibit greater deviation from the course of the lead vehicle and run the risk of leaving the lane. By contrast, having the lead vehicle send positioning information to all following vehicles for use as a

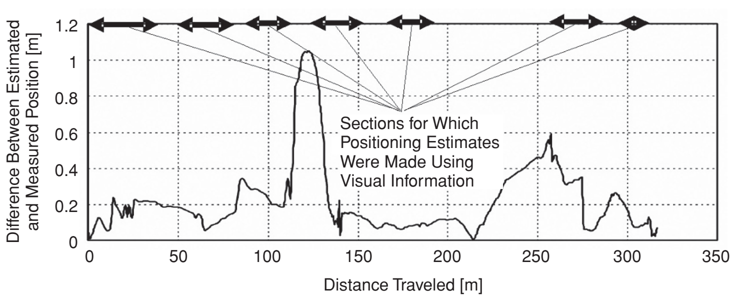

Fig. 7 Estimate of position using visual information

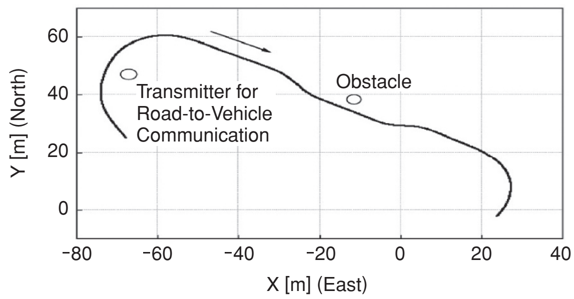

Fig. 8 Vehicle driving route when avoiding obstacles

target route, all vehicles are able to follow the route of the lead vehicle regardless of their order in the group.

The authors constructed a vehicle tracking system for welfare vehicles designed to reduce the driving burden for people lacking full use of their hands. Under this system, a manually driven vehicle constantly transmits, using vehicle-to-vehicle communication, positioning information obtained through RTK-GPS. When the welfare vehicle with tracking function approaches the rear of the manually driven vehicle it receives positioning information and is capable of following. The driver of the welfare vehicle can then press a button to make it automatically follow in the path of the manually driven vehicle at a given distance.

In addition, it has been demonstrated that road-to-vehicle transmission of detailed obstacle positioning information can make obstacle avoidance possible. Transmitters on the road send both detailed obstacle position information and information on obstacle avoidance routes to an automatic driving vehicle using RTK-GPS. The automatic driving vehicle avoids the obstacle by using the obstacle avoidance route information. This method would be effective in enabling automatic driving vehicles to avoid damaged vehicles or road construction sites that occupy their lanes for extended periods of time. Figure 8 shows the results of an obstacle avoidance experiment: the path of a vehicle avoiding an obstacle based on information received from a roadside transmitter.

3. AUTOMATIC DRIVING WITH STEER-BY-WIRE VEHICLES

This section describes efforts to exploit the advantages of steer-by-wire vehicles for automobile lane keeping by applying them to automatic driving. The following subsections describe research in the application of steer-by-wire to automatic driving, including research on switching between automatic driving and manual driving in steer-by-wire vehicles and automatic lane keeping control consistent with both driver override and highly accurate lane keeping.

3.1 Automatic/manual driving switching control

In conventional automobiles, the driver's input device (the steering wheel) and the automobile's steering gearbox are mechanically linked, meaning that exercising control over the steering angle also necessarily controls the driver's steering wheel. Therefore, switching between manual and automatic driving can create friction between the driver and the system. With steer-by-wire vehicles, however, there is no mechanical link between the steering wheel and the automobile's steering gearbox so it is possible for them to maintain separate angles. The authors, focusing on this feature, added the steering angle calculated by the lane keeping controller with the driver's steering wheel angle in a certain ratio – generating the actual steering angle – and then varied this ratio to attain smooth switching between automatic and manual driving. The upper section of Figure 9 presents test results when switching from manual to automatic driving. The lower section of Figure 9 presents test results when switching from automatic to manual driving. Here, the actual steering angle = R (the steering angle as calculated by the system) + (1-R) (the driver's steering wheel angle), where R is varied from 1 to 0 or 0 to 1. When R is 1 the vehicle operates under fully automatic driving; when R is 0 it is fully manual. Figure 9 indicates the relationship between time as R is varied from 0 to 1 or 1 to 0, vehicle yaw rate and lateral displacement from the target lane. Although there is a large yaw rate when the switching time is 0, the results illustrate that taking more than two seconds to switch enables a smooth transition between automatic and manual driving.

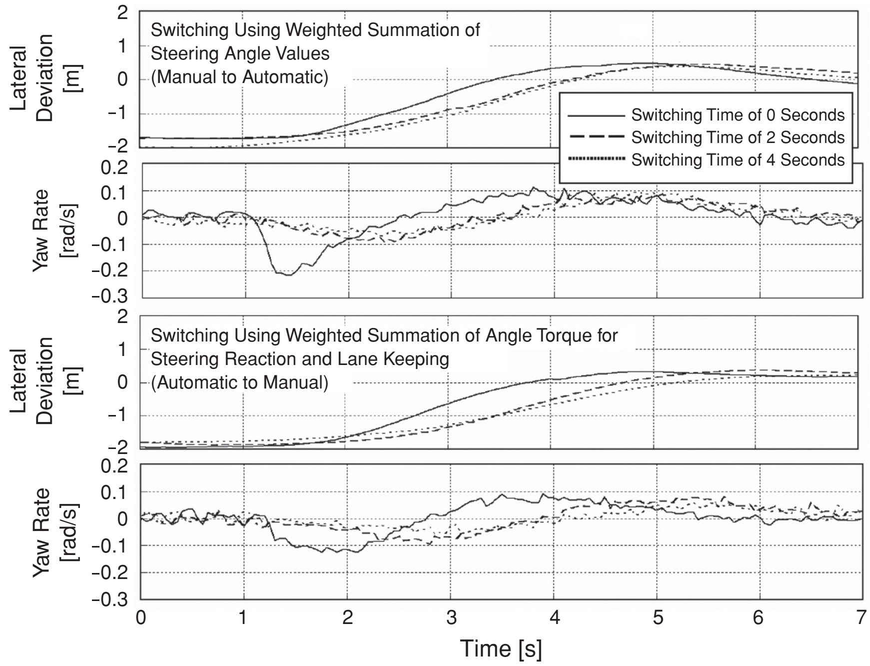

Fig. 9 Switching between automatic/manual driving using weighted summation of steering angle values

3.2 Automatic lane keeping control consistent with both driver override and highly accurate lane keeping

When considering lane-keeping with automatic driving and steer-by-wire vehicles, one can think of both the steering wheel's feedback producing motor (feedback motor) and the motor that drives the steering link (steering motor) as outputs for the steering angle, or steering torque, calculated by the lane-keeping controller. When controlling only the feedback motor, the steer-by-wire controller controls the steering link based on the steering wheel angle thereby obtained. In this situation, the driver can override the system by turning the steering wheel in a way that resists the feedback motor. However, when the torque of the feedback motor's output shaft is low, control of the steering wheel angle can be sluggish, making highly accurate lane keeping difficult. At the same time, controlling only the steering motor enables a higher-speed response but nullifies driver operation of the steering wheel, making override difficult and potentially making the driver uneasy.

The authors, therefore, proposed and evaluated a lane keeping method that controls not only the feedback motor but also the steering motor to achieve high-speed reaction unattainable using the low-torque feedback motor alone and consistent with both driver override and highly accurate lane keeping. Specifically, the target steering angle was defined as the target value and both the feedback motor and steering motor were controlled simultaneously. However, if the target steering angle for the steering motor exceeded the steering wheel angle ± stipulated value , the target value was controlled as steering wheel angle ± . A graphic description of this method appears on the right side of Figure 10. The limiter in the figure restricts input to + or - in the event that it exceeds ± . The right side of Figure10 illustrates this method by picture, where the steering wheel shaft and steering gear shaft are mechanically connected with a clearance of . However, the movement of the steering gear shaft has no effect on the movement of the steering wheel shaft. Because the steering motor can move independent of the steering wheel angle within this clearance range of ± , it is possible to compensate for delay in steering wheel angle reaction and perform minute steering beneath the steering wheel angle's control resolution. In addition, if the driver turns the steering wheel during control, the steering angle will react with difference of the clearance of . In other words, driver override is possible.

Figure 11 presents the results of an experiment conducted to evaluate the relationship between and tracking accuracy. It indicates the relationship between when driving on the test course and the RMS value of the vehicle's lateral displacement from the target lane. An in-

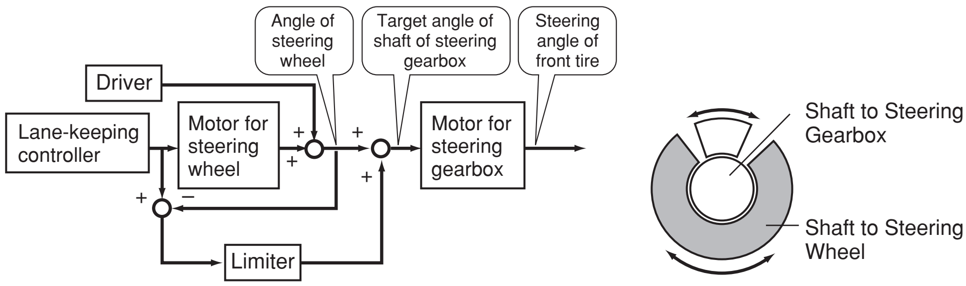

Fig. 10 Control consistent with both driver override and highly accurate lane keeping, and a pattern diagram thereof

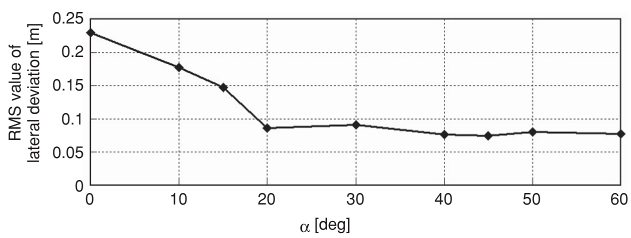

Fig. 11 Relationship between and tracking accuracy

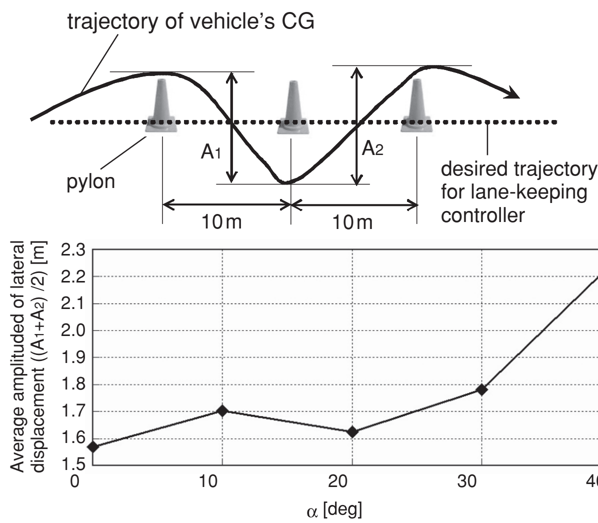

Fig. 12 Relationship between and ease of override

crease in leads to improved tracking accuracy but beyond an of 20 degrees there is little change. In other words, highly accurate lane keeping can be achieved with an of 20 degrees or more.

Figure 12 presents the results of an experiment conducted to evaluate the relationship between and ease of override. Pylons were placed on the automatic driving route as depicted in the upper portion of Figure 12 and drivers instructed to avoid the pylons, but pass as close to them as possible, by overriding the system. The lower portion of Figure 12 represents an evaluation of the amplitude of vehicle lateral displacement, with lower averages of A1 and A2 representing better avoidance. As the lower portion of Figure 12 shows, when exceeds 30 degrees the average of A1 and A2 increases, suggesting greater difficulty in vehicle handling. In other words, driver override can be considered possible provided is less than 30 degrees. These results confirm that, within the scope of the experiment, an of at least 20 degrees enables highly accurate lane keeping while an less than 30 degrees enables driver override. Because a smaller is preferable as long as highly accurate tracking is possible, an of 20 degrees can be said to enable lane-keeping control that is consistent with both driver override and highly accurate tracking.

4. EVALUATION OF DRIVER BEHAVIOR DURING AUTOMATIC VEHICLE DRIVING

This section describes research on the evaluation of driver behavior during automatic driving. As part of our research into the human factors of automatic driving systems, we evaluated driver reaction time when steering control suddenly malfunctions during automatic driving and the vehicle leaves the lane[31]. Details of the experiment and our findings are described below.

4.1 Experimental conditions

In the test scenario the test subject boards the automatic driving vehicle alone and shifts into drive, upon which automatic driving commences. After initiating automatic driving, the vehicle proceeds to circle a loop course. During automatic driving the steering wheel suddenly exhibits abnormal rotation and the vehicle begins to diverge from the lane formed of pylons. The experiment evaluated the time between the moment when the steering wheel began to rotate abnormally and the moment when the test subject noticed the abnormality and reacted by engaging the brake or steering wheel. Tests were conducted four times for each test subject, with the steering wheel rotation abnormality occurring either 5, 10, 30 or 60 minutes after the start of each test. The steering wheel rotation abnormality occurred on the straight part of the course, with the steering wheel angle rotating up to 500 degrees to the right at a rate of 270 degrees per second.

A short loop course on campus was used with vehicles running at a low speed of 10 to 15km/h for safety reasons. Automatic driving and triggering of the abnormality were conducted using a remote control device developed for this experiment. In other words, although test subjects were told that the vehicles would be driving automatically, they were actually controlled by remote operators.

Test subjects were provided with the following instructions in advance:

- The experiment is a test of an automatic driving system;
- The vehicle will perform automatic driving;
- The destination will be reached in just over an hour, when the vehicle will stop in its lane;
- Steering abnormalities, sudden acceleration, sudden braking, mechanical abnormality in the actuator connector or system failure may occur during automatic driving; and
- Please ensure safety by monitoring safe driving until you reach your destination and prepare to cope with any abnormality by engaging the brakes or steering wheel.

4.2 Experimental results

Test results are summarized in Figure 13, categorized as the period of time between the moment the steering wheel angle reaches 60 degrees and either the moment the driver notices the abnormality and begins to move his feet or hands (reaction time) or the moment the test subject's action has an effect (execution time). Execution time was measured, when engaging the brakes, as extending to the moment when the hydraulic sensor in the master cylinder indicated about 20% the pressure of stepping firmly on the brake (about 25kgf/cm^2). When engaging the steering wheel, it was measured as extending to the moment when the test subject returned the steering wheel to zero degrees. When both operations took place, the time for the action completed earlier was used.

Figure 13 indicates reaction time and execution time by drive time for 30 test subjects, including average, standard deviation, maximum and minimum values. As these results show, values were very similar when drive time was 5, 10 or 30 minutes, with an average reaction time of 0.6 to 0.7 seconds and an average execution time of 1.1 seconds. Standard deviation was also small. On the other hand, when drive time was 60 minutes the average reaction time was 1.2 seconds and the average execution time was 1.9 seconds, values nearly double those for 5 to 30 minute drive times. Standard deviation was also more than double that for 5 to 30 minute drive times. In other words, there was a tendency for longer reaction and execution times with longer drive times, as well as more pronounced individual variation.

Figure 14 provides examples of test subject behavior observed during automatic driving. Test subjects were informed of both the potential for abnormalities in the automatic driving system of the vehicle in which they rode and what kind of abnormalities they might expect and were asked to respond to such abnormalities by engaging the brakes or steering wheel. Although some test subjects remained ever ready to respond in the event of an abnormality, other test subjects, despite their awareness of the potential for problems, manipulated their mobile phones, slept or read while riding. Some test subject were observed crossing their legs or otherwise assuming positions from which it would be difficult to engage the brakes promptly. For the 60-minute period of automatic driving, 8 of 30 test subjects fell asleep during the experiment. Looking at the behavior of the 11 test subjects whose reaction time to the abnormality was 1.5 seconds or more, 4 had been doing nothing in particular, 3 had been reading documents or magazines, 3 had been sitting cross-legged and 1 had been composing mail on a mobile phone. While the slow reaction of those who had been doing nothing in particular may be attributable to decreased alertness, in this experiment slow reactions were more often attributable to other causes.

The experiment confirmed that driving using automatic driving for long periods of time leads to longer reaction and execution time and greater individual variation. Long periods of automatic driving not only led to decreased attentiveness and situations where drivers actually fell asleep, but the boredom of sitting alone with nothing to do also led drivers to engage in a variety of behaviors. Test results suggest that when drivers are asked to monitor an automatic driving system or conduct a switch from automatic to manual operation, it is necessary to consider the effect of drive time and the possibility that,

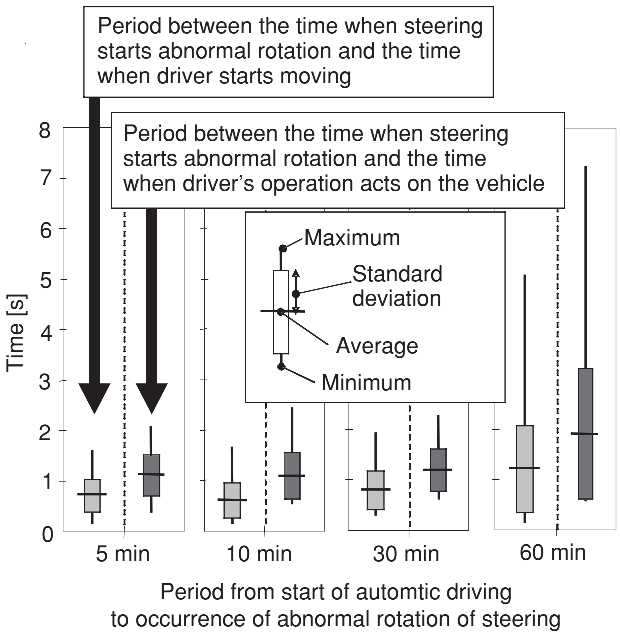

Fig. 13 Driver reaction time to steering control abnormality by drive time

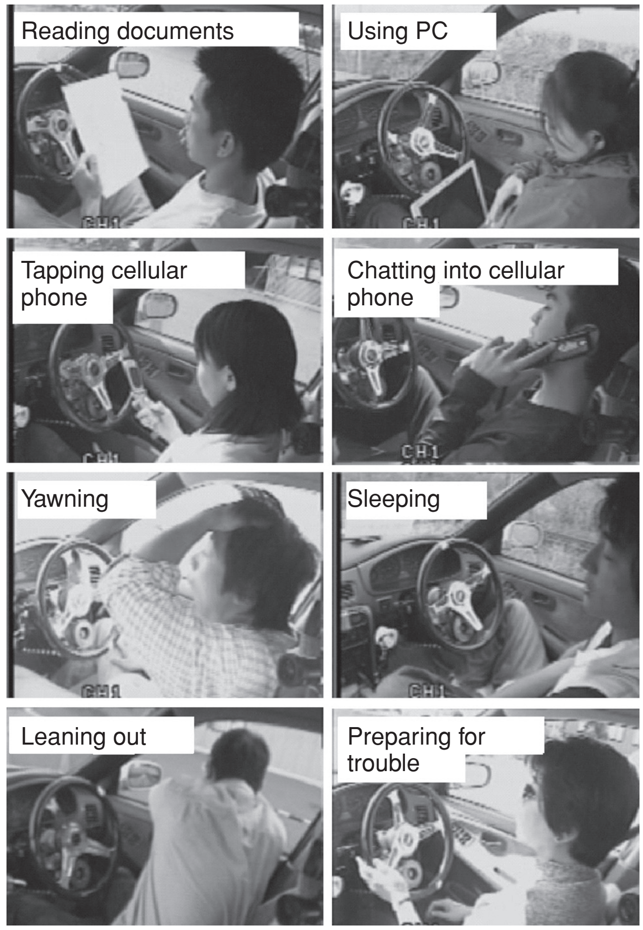

Fig. 14 Driver behavior observed during automatic driving

even when alert, drivers may be manipulating their mobile phones or reading rather than looking ahead or at the instrument panel. In addition, in terms of operability, there is also a need to consider that drivers may cross their legs, kick off their shoes or hold something in both hands, making it impossible to quickly engage either the steering wheel or the brakes. In addition to these possibilities, making drivers responsible for monitoring is also subject to the issue of social acceptability. Of the 30 test subjects, 23 responded negatively when asked if they would like to use an automatic driving system that requires monitoring by the driver. Simply sitting in the vehicle monitoring the system is extremely tedious and there is a strong probability that automatic driving that requires monitoring by the driver would be difficult for society to accept.

5. CONCLUSION

This paper has reported on research in the use of RTK-GPS and steer-by-wire in automatic vehicle driving control and research on human factors involved in automatic driving.

Control based on RTK-GPS positioning information, which enables conversion of the objects to be followed or avoided into numerical data for transmission, expands the possibilities for automatic driving functionality. At the same time, it is not possible to obtain high-precision measurements at all road locations. A number of methods must be combined to increase the reliability of the system and maintain safe driving even in environments where measurement is impossible.

Steer-by-wire offers tremendous flexibility in the automatic driving interface between driver and vehicle. Nevertheless, control systems must be designed with care to ensure that behavior that differs from conventional vehicles does not invite driver anxiety or improper operation.

In considering the human factors of automatic driving, there is a need for a variety of evaluations given that drivers are not highly trained like airplane pilots but are men and women of all ages who represent a broad spectrum of individual differences.

Given continued advances in body, sensor, telecommunication and information processing technologies, we hope to continue our tireless work developing and evaluating safe, pleasant and reliable automatic driving systems.

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